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If Our Robots Are So Smart, Why Aren't We All Rich?

(The Challenges of Integrating Autonomous Robots)

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CIRA '99
Monterey CA, 8 November 1999

Report Documentation Page

Form Approved OMB No. 0704-0188

1. REPORT DATE **NOV 1999**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **If Our Robots Are So Smart, Why Aren't We All Rich?**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Douglas W. /Gage**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Space and Naval Warfare Systems Center San Diego, CA 92152-7383**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**42**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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Why bother to sell ROBOTS when you can sell robot STOCK?

Denning Mobile Robotics has yet to build a robot. Why bother, when shareholders seem mesmerized by its power of suggestion?

Beep, beep . . . buy this stock

This is a good example of why we need to understand what we are dealing with —

By John A. Byrne

THE IDEA IS PURE *Star Wars:* Sell sinister-looking robots to guard prisons and industrial buildings. Denning Mobile Robotics, Inc. went public with this concept last summer, and investors gobbled up the penny stock offering. They paid $3 million for one-third of the company.

In January the *Wall Street Journal* and other publications reported that Denning had landed a $30 million contract to supply robots to Southern Steel Co. Share prices zoomed. A Denning unit (comprising one share of common and two warrants to buy more stock later) now sells for about 59 cents, quite a rise from the 10-cent offering price. Controversial stock picker Ray Dirks thinks bigger gains are in store. "Denning is my pick for 1984," he proclaims.

But

The company's spare headquarters outside Boston, however, is anything but glamorous. Denning operates out of a shabby industrial building, one flight down from a contract bridge school. Visitors must sign secrecy agreements, and a warning reads "Escort Required Beyond This Point." That's puzzling because there are no robots inside, just some things that look like garbage cans on wheels.

Enter R. Warren George II, Denning's intense 37-year-old founder and president. He explains that he previously worked as a Washington lobbyist for Foster-Miller Associates, a small machinery designer. He left the company in 1981, he says, because he wanted to get into a high-technology business. A Foster-Miller spokesman remembers things differently. She says George was axed in a staff reduction.

Denning's founder has other background problems—which he admits when confronted by FORBES with the facts. George has led colleagues and investors to believe he holds three degrees, including an M.B.A. from Babson College and an MIT master's in materials. Neither institution has a record of his attendance. What about his days at the University of New Hampshire? The school says he never graduated, though he was a student for six years.

Of course, it doesn't take a diploma to run a business. After a friend suggested that he look into robotics, George wrote a proposal and made a pitch to 75 venture capitalists. No takers. Denning is a pioneer, explains

FORBES, APRIL 23, 1984 35

… already been tried!

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So the real answer is...

- We aren’t all rich because nobody is buying a lot of smart robots.
- Nobody is buying a lot of smart robots because a robot that a lot of people would want to buy would have to be useful and/or entertaining, inexpensive enough for people to afford, and be perceived to be worth its price. Simply being “smart” doesn’t matter.
- So the REAL answer is actually question: “How can we build smart robots that are (1) useful and/or entertaining, (2) inexpensive enough for people to afford, (3) perceived to be worth their price?”

Outline

- The SPAWAR perspective on robotics
- Polemical remarks
  - A cynic's view of robotics research
  - Lessons from MDARS-I
  - Sensing, perception, and navigation in humans and robots
  - Lessons from the Past? ALV, speech recognition
  - Limits of the biomimetic approach
  - "Irrelevant Algorithm Syndrome"
- Brief Case Study: the DARPA Tactical Mobile Robotics (TMR) Program
- Need both tight integration and maximum flexibility
- Conclusion: Economics rules in the Next Millenium!

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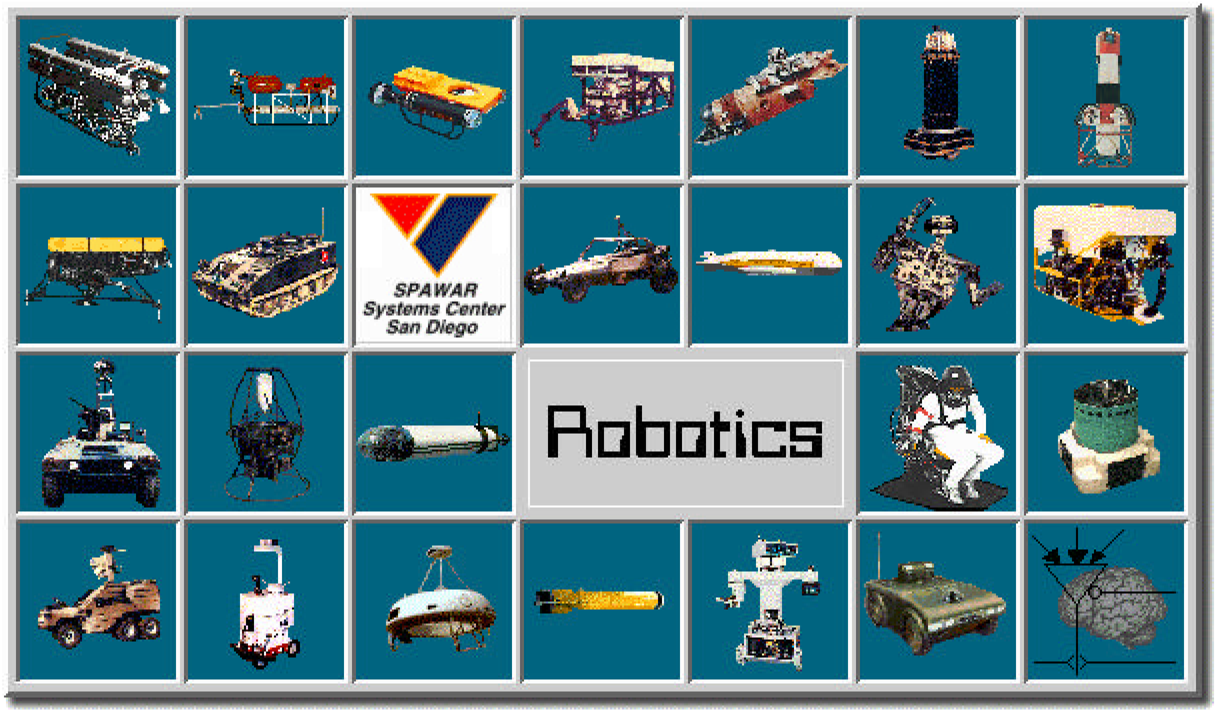
http://www.spawar.navy.mil/robots/



Space and Naval Warfare Systems Center
(formerly NELC, NUC, NOSC, NRaD)
UUVs since early 1960s, UGVs since early 1980s
Prototype system development, not "basic research"
Many technical papers on line at above URL

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Robotics Development Process

(Effort required is proportional to area)

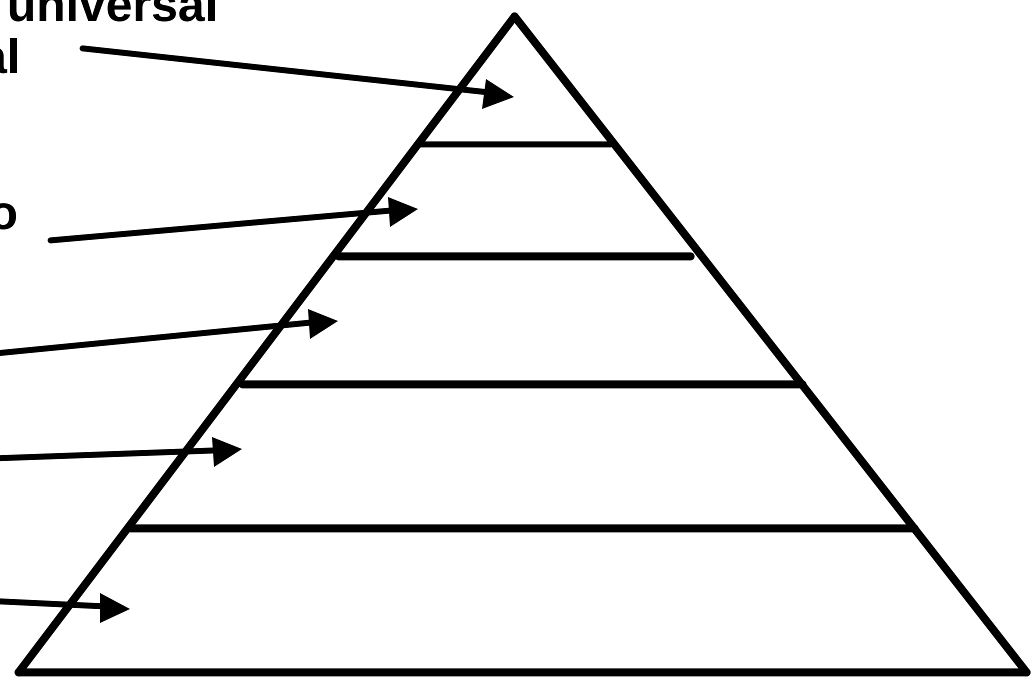
Development of brilliant universal overarching architectural scheme

Application of scheme to a specific robot design

Detailed design

Implementation

Debugging and demo prep



Bottom line: definitely 1% inspiration, 99% perspiration!

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The Downside Risk:
A Cynic's View

GOAL

To explore the possibilities and implications of a proposed innovative behavior/control/navigation architecture/system

APPROACH

To implement a physical robot to serve as a testbed and demonstration platform

WHAT IS LEARNED

Alkaline batteries are good

Rechargeable batteries work best when actually recharged

Connectors and cables are failure prone

Sensors are "unreliable"

Whatever monitoring tools were implemented in the systems aren't good enough to tell what's "broken" when "it doesn't work"

A cut-up cardboard box can keep the sun off a monitor screen

You never have enough batteries for your digital camera

Alan Alda’s comments from “Natural Born Robots”

- **“…but while I was there it was barely able to lurch to its feet.”**
  - **re Case Western Reserve giant pneumatic cockroach**
- **“And so a sinking robot pike joins the stubborn robot cockroach in demonstrating just how hard it is to copy mother nature.”**
  - **after MIT’s “Robo-pike” developed a leaky “head-gasket”**
- **“I’m beginning to wonder if I’m some sort of robot jinx.”**
  - **after a motor failed on MIT’s “Spring Flamingo”**

  - **from Scientific American Frontiers: Natural Born Robots (show 1002), on PBS, 2 November 1999**

General Lessons Learned From MDARS-I (1)

Moving a robot from one environment to another invites unanticipated problems; typical causes include:

- hardware and software errors that haven't been manifested in the previous environment
- sensor modes or processing algorithms tuned too tightly to specific characteristics of the initial development environment
- unexpected breakdowns due to subtle interactions between multiple hardware and software components

A well implemented adaptive behavior can mask faults; should instrument behavior to report a problem such as steering that constantly "pulls left"

General Lessons Learned From MDARS-I (2)

If a complex robot is to operate robustly, its world model must take adequate account of the relevant dimensions of variability of the environment, as they will be reported by the sensor subsystems.

- **A robot's world model is <u>much</u> simpler than a human's**
- **Unintended aspects of the model can creep in as consequences of various software design decisions**
- **The developer must understand the limits of his system's world model**

Behavioral robustness is required if mobile robots are to find viable markets; the designer must accommodate the full range of variability within:

- **manufacturing processes: no handcrafting**
- **target operating environments: no manual "tuning"**

General Lessons Learned From MDARS-I (3)

Expect the unexpected!

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Human Perception-based Navigational Capabilities

Every human naturally acquires the skills to

- **avoid bumping into anything while moving**
- **understand where he or she is trying to go**
- **figure out how to get there**

Humans are therefore able to accept and execute tasking presented in terms like:

> **"Go down this road about a mile and turn left on Union Street --it's the second or third light, I think -- and then turn right into the alley just past the McDonald's; it's the second house on the left, the green one with an elm tree in front -- you can't miss it."**

One key is that a human can detect, localize, classify, and identify <u>specific</u> environmental features:

- **under widely varying environmental conditions**
- **independent of relative orientation and distance**

But a <u>robot's</u> perceptual capabilities are extremely limited

<u>Sensing</u> is NOT necessarily <u>perceiving</u>

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The Distinction Between Sensing and Perception

Robotics researchers, being human, are so completely immersed in the world created by our vision-oriented perception capabilities that we tend to mistake it for the actual physical world around us, and are therefore constantly surprised and disappointed by the comparatively pitiful capabilities of our robots' sensors.

Practical and affordable sensor systems simply do not provide enough accuracy or resolution to make up for a robot's lack of human-level perceptual processing.

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To the inventor of the hammer, everything looks like a nail...

DOD Targets 3 Projects For AI, Supercomputer Uses

By Chappell Brown

BOSTON — Lynn Conway, assistant director of strategic computing for the Department of Defense, outlined a broad-based program here last week to apply artificial intelligence and supercomputer technology to military systems.

Congress has approved $50 million in funding in fiscal 1984 for an initial project that targets development of three military artificial intelligence systems by technology and applications "communities," Conway said.

Projects Described

Conway, speaking at a VLSI conference at the Massachusetts Institute of Technology, said the systems to be developed initially include an autonomous land vehicle, a personalized adviser for jet pilots and an aircraft battle-management system.

Though Conway did not go into details about each project, in the past the Defense Department has said that the military would like a land vehicle that could roam a battlefield and detect enemy troops or equipment. The jet pilot's "adviser" will be an expert system giving instantaneous advice to jet pilots during flight, and a computerized battle management system would coordinate attacks from an aircraft carrier.

Military Applications

Conway said development of these systems would provide the basis of a "strategic computing" program that would develop technology of "unprecedented capabilities."

The program will focus on military applications that require machine intelligence and will draw on recent advances in computer vision, speech, and expert system technology.

Expert systems are a branch of artificial intelligence research that use databases derived from the experience of human experts to draw inferences in novel situations.

Conway used an incident in the Falklands war as an example, illustrating the use of this kind of system in a battle.

Falklands Incident Cited

British ships were using a computer-controlled radar system as a defense against Argentine aircraft. Although the system was highly advanced, the Argentinian pilots found a ploy that would confuse the system—they would fly in a tight pattern, appearing as a single object to the radar, and then quickly disperse.

This unexpected maneuver confounded the computer-controlled system. The experts needed to reprogram the system were all back in Britain.

What was required was an instantaneous expert at the scene, or, even better, a system that was more adaptable to novel situations, Conway said.

There are three broad technological goals of the strategic computing program: to provide the United States with a broad-based machine intelligence capability, demonstrate applications important to defense and provide technological spinoffs.

A fundamental theme of the project will be the interaction of advanced areas of research. For example, advanced VLSI architectures need to be combined with the kind of software and systems work being undertaken by artificial intelligence researchers. At this time, research groups such as these are not coordinated, Conway pointed out.

Applications 'Pull'

In Conway's view, specific programs—such as developing an autonomous land vehicle—impel this kind of cooperation; she spoke of applications providing the "pull" needed to create machine intelligence.

Although DARPA (Defense Advanced Research Projects Agency) will manage the project, approximatly 10 "computer technology communities" will be created to develop the required technology and another five to 10 "applications communities" will work on implementation. Each community will involve 100 professionals from private, academic and government areas.

A high degree of interactivity will be crucial to the project, and networks and interactive workstations will be heavily used. Conway used the phrase "an online window into activities."

Although the need for secrecy on defense projects might work against this open communications network, Conway replied that only the specific applications communities would be operating under classified information restrictions. The basic technology development program would be open.

The plan calls for $50 million in 1984, $96 million in 1985 and $150 in 1986.

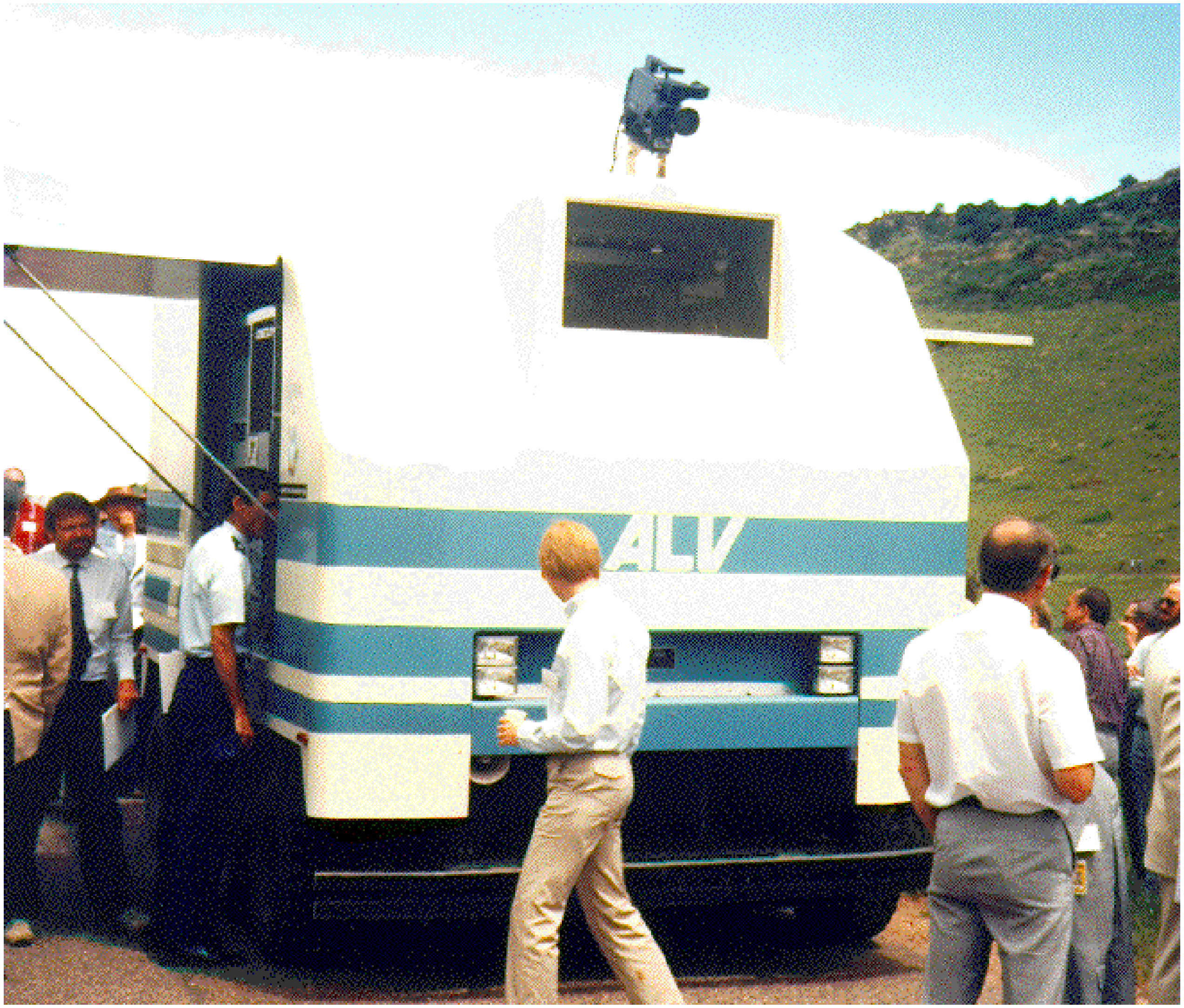
Japanese Reveal VLSI Thrusts

By Chappell Brown

Apple: Mac Won't Repeat

(announcement of DARPA ALV program, January 1984)

Autonomous Land Vehicle (ALV)



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A Lesson from ALV?

- Autonomous Land Vehicle began in 1984, with goals that arguably have not yet been realized 15 years later
  - Not from want of trying: Demo II, Demo III, others
  - 15 years of Moore’s Law progress: factor of 100 to 1000
- If we were that far off in assessing the difficulties of the problem in 1984, what makes us think that we are any smarter today?

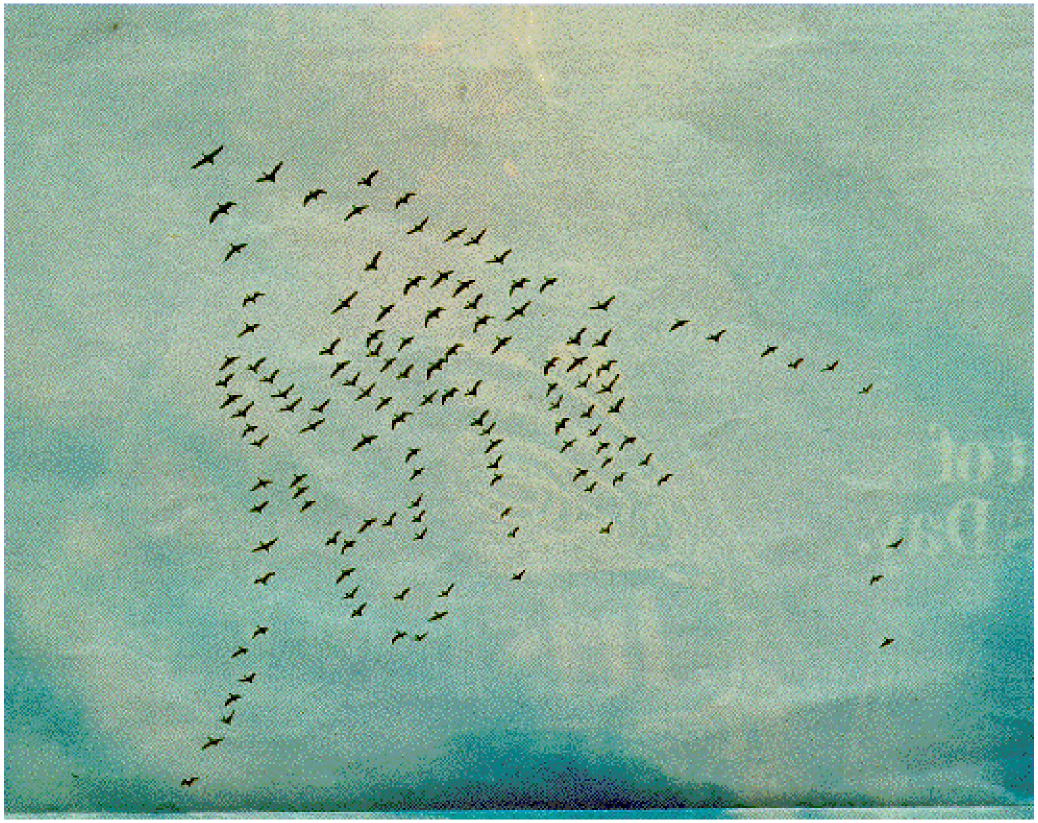
“Whither Speech Recognition?”

- **J. R. Pierce, Bell Labs, Letter to the Editor of Journal of Acoustical Society of America, 1969:**
  - **“Most recognizers behave, not like scientists, but like mad inventors or untrustworthy engineers. The typical recognizer gets it into his head that he can solve “the problem”. The basis for this is either individual inspiration (the “mad inventor” source of knowledge) or acceptance of untested rules, schemes, or information (the untrustworthy engineer approach)…**
  - **“The typical recognizer… builds or programs an elaborate system that either does very little or flops in an obscure way. A lot of money and time are spent. No simple, clear, sure knowledge is gained. The work has been an experience, not an experiment.”**
  - **JASA Volume 46, Number 4 (Part 2) 1969, pp 1049-1051.**

Biologically Inspired Systems

- **A biological system is evolved, and does just what it does. It is not necessarily the "existence proof" for something "similar" that would be "useful"**
  - **Lacks a well defined "control interface" to modulate system goals**
  - **Implemented as opportunistic collection of special cases**
  - **Implementation layering is imperfect**
- **Implication: opportunities for exploitation of biological approaches have well defined limits**
  - **Effectiveness and efficiency: automobiles have wheels, not legs, airplanes don't flap their wings like birds**
  - **Physical evolution generally too expensive in terms of time and resources**

“Now that’s flying first class”



(1990 advertisement for 100% Colombian coffee)

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Irrelevant Algorithm Syndrome

- **Generally manifested as simulation (or "toy" demo) totally decoupled from reality**
- **Case 1: "Fantastical" sensors**
  - **Group foraging algorithm using sensor that reliably provides the distance and direction to the "nearest food item"**
  - **Formation algorithm using sensor that reliably provides the distance and direction to the <u>farthest</u> member of the group**
- **Case 2: Unrealistically precise sensors**
  - **Perfect landmark detection, identification, tracking**
- **Exception -- a new sensor that provides a truly revolutionary capability**
  - **Sick laser rangefinder that "cut the Gordian knot" for indoor mapping**

Tactical Mobile Robotics (TMR)

- DARPA Advanced Technologies Office (ATO)
- Initiated by Dr. Eric Krotkov in 1997
- Program Manager is LTC John Blitch
- BAA 98-08, BAA 97-20, BAA 96-26, SBIRs, etc
- Principal Agent is TACOM-TARDEC
- SPAWAR provides technical guidance

  – See E. Krotkov and J. Blitch, "The DARPA Tactical Mobile Robotics Program", The International Journal of Robotics Research, Vol. 18, No. 7, July 1999, pp. 769-776.

The Technical Goal of TMR

Development of a system of robots capable of

operator-tasked and -monitored

perception-based

autonomous mobility

in diverse unstructured environments

that can fit into a rucksack

and be employed in coordinated groups

as a tool for the dismounted warfighter

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TMR Constraints

Characteristics necessary for a robot to fulfill the TMR role

Constraints as opposed to system deployment concepts

- Users will be imaginative in finding many uses for TMRs

Fit in a rucksack (size, weight, compete with rations, ammo, etc.)

Climb upstairs, downstairs, clamber over rubble

Maintain constant communications (with users, other TMRs)

Navigate based on intuitive operator direction; not get lost

Accept and require appropriate level of operator interaction

- Support precise control when desired (e.g., blow mousehole)
- Offer ZERO distraction to warfighters in heat of battle
- Don’t get in the way or slow OPTEMPO

TMR Technology Wish List

- **Well defined capabilities**
  - – Power source: higher energy density, power density
  - – Processing: higher MIPS per mass/volume/power
  - – Sensors: higher resolution, range; lower size, weight, power
  - – Communications anywhere: unimpeded through matter
    - »higher B/W: video -> color -> stereo -> omnidirectional
  - – Localization: equivalent of CP-DGPS anywhere
- **Subtler capabilities**
  - – Locomotion schemes: go anywhere
  - – Perception: obstacles, landmarks, threats, friends, etc
    - »detect, classify, identify, localize, track
  - – "Effective and efficient" operator interface
  - – Sensor-guided mobility

TMR Phase I Core Performers

BAA 98-08 Part A Performers (Technology)

- **Mobility: MIT**
- **Sensors: U Michigan**
- **Perception: Yale, SRI Intl**
- **Autonomy: SRI Intl, CMU, Stanford, USC, Georgia Tech**
- **Mission Packages: Foster-Miller**

BAA 98-08 Part B Performers (System Design)

- **SAIC, Draper Lab, Raytheon**

BAA 97-20 Phase II Performer Team

- **Jet Propulsion Lab (lead), CMU (navigation), IS Robotics (mobility), Oak Ridge National Lab (group behaviors), USC (OCU)**

(plus SBIR and other ancillary participants)

If TMR Is So Hard, Why Do We Think We Can Do it?

- Moore’s Law (processing availability)
  - >10**3 gain beyond ALV era
- Rapid <u>commercialization</u> of relevant technologies
  - Wireless communications
  - GPS navigation
  - Display technology and HDTV
  - MEMS and fiber optic based sensors
- New mobility capabilities (e.g., “Urbie”)
- Use of operator’s perceptual capabilities to offset robot’s functional/ performance deficiencies
  - TMR autonomy goals well-defined, limited
  - Flip side of “robot as tool”

Evolving Technology Area: Range Measurement (1)

- **Used for obstacle avoidance, mapping**
- **Ultrasonic**
  - mature technology (1980?), inexpensive
  - low angular resolution, limited range
  - rough 2-D map of nearby empty space
- **Structured light**
  - mature technology, no academic interest, but few if any COTS subsystems
  - triangulation of laser stripes
  - active, limited range
- **Laser line scanner**
  - Sick (German) industrial unit: heavy, expensive
  - high angular and range resolution, longer range
  - precise 2-D map of empty space

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Evolving Technology Area: Range Measurement (2)

- **Stereo vision**
  - uses only cameras (e.g., CMOS) + processing (Moore's Law)
  - 3-D range map of nearby surfaces (passive)
  - needs visual texture, errors are 1/r**2
- **Scanned LADAR**
  - expensive, bulky, moving parts
  - 3-D range map of surfaces (active)
  - error constant with range
- **Flash LADAR**
  - 1-5 years away (driven by auto market)
  - range, resolution limited by laser power on pixel
  - compact, inexpensive

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TMR-Specific Challenges

- Acquiring critical non-robot-specific component technologies
  - power, displays, communications, etc
- Being small enough and big enough
  - Implementation fitting in rucksack envelope
  - Achieving functionality, performance
- Supervised autonomous navigation
  - How operator tasks, monitors, overrides
  - How robots actually execute moves
- Implementation: making it all actually work
  - Robotic system decomposition/architecture(s)

TMR Evolutionary Strategy for Achieving Autonomous Navigation

- **Supervised perception-based navigation commands**
- **Path-referenced navigational functions**
- **High-level mission-oriented autonomous tasks**
  - **(Multiple coordinated robots)**
  - **Mapping and monitoring building interiors**
  - **Adaptive maintenance of communications connectivity**
  - **...**

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TMR Supervised Perception-Based Autonomous Navigation Capabilities

- **Goal: maximize system performance for the available level of perception capability**
- **Build on visual servoing**
- **Add semantics of intent/environment**
  - **Analogous to indoor ultrasonic-based schemes (e.g., wall-following, hall-following, lateral post detection) and to vision-based road-following**
- **Add mission scripting**
- **Add tools for operator oversight/override**
- **Exploit future advances in machine perception**

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Perception-Based Navigation Commands

- Move Under <this> Vehicle
- Climb <how many> Flights Up <these> Stairs
- Climb <how many> Flights Down <these> Stairs
- Take <this> Elevator to the <number> Floor
- Cross <this> Street (and don't get hit)
- Hide in <this> Vegetation
- Move Along <this> Wall (until…)
- Open <this> Door (and Enter… and Close)
- Move in <this> Direction (until…)
- Wait until… (humans are (not) present…)

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A Complex Command Behavior: Using an Elevator

- Take <this> elevator to the <number> Floor
  - No people present --> many people present
  - Single elevator --> double bank of elevators
- Issues
  - Manipulation: reach, strength, tactile/haptic feedback
  - Sensor viewpoint (e.g., be able to see indicators above door)
  - Perception: “understand” controls, indicators, auditory cues
  - Task planning, execution, monitoring: Press Up or Down? Get into this elevator? Press which floor button? Get off here?
- A “good” challenge
  - A useful real world human task with a good blend of complexity and structure, an easy tasking paradigm, and ease of testing

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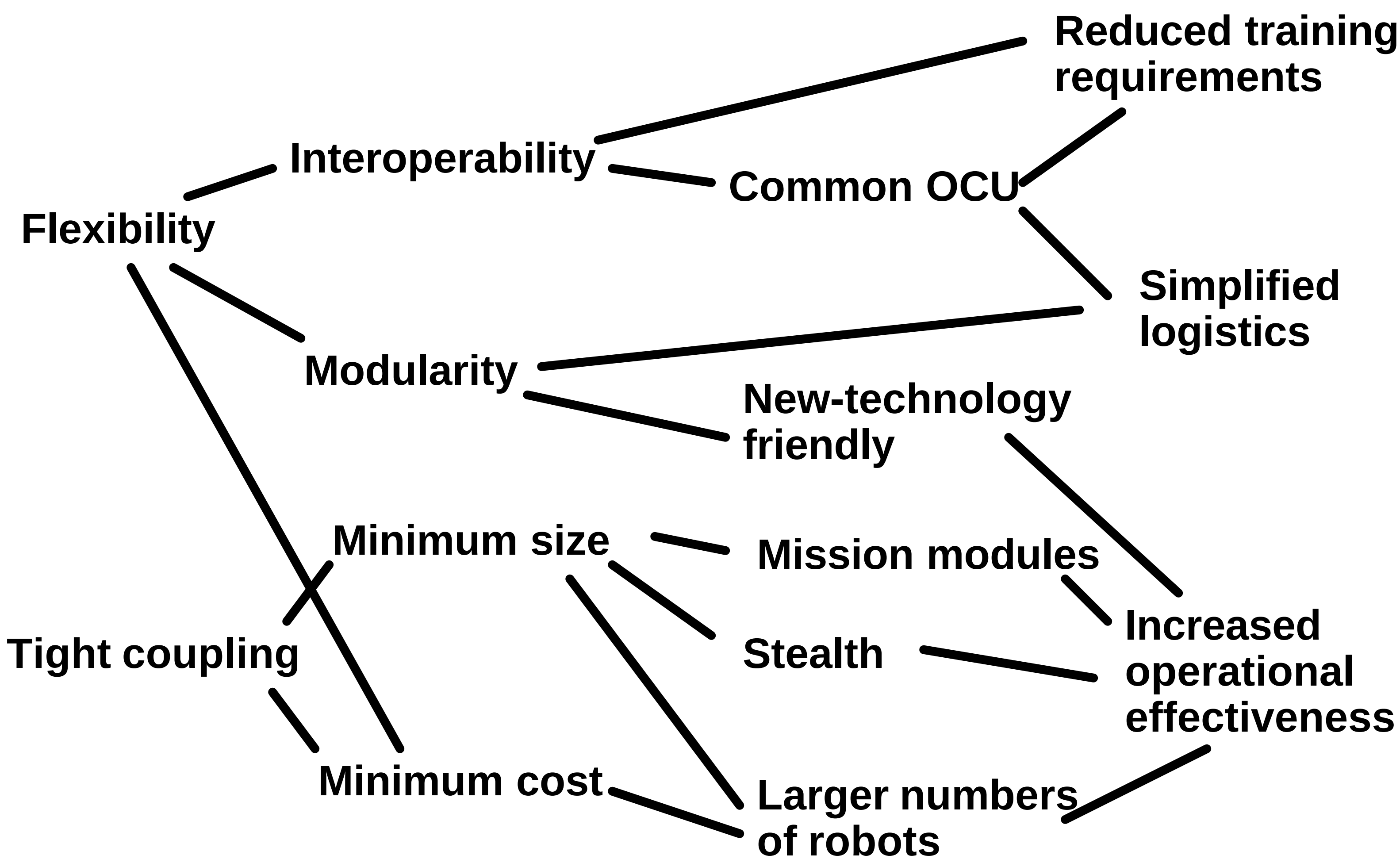
Path-Referenced Navigation Capabilities

- “Been There, Done That”
  - Follow the leader (without interfering)
  - Route replay
  - Retrotraverse
  - “Go back to <this> previous location” (how to specify?)
- Big operational payoff
  - Tasking in terms of mission events
  - Classic “what do you mean you can’t…” stuff
- DGPS Based --> Perception-Based
- System level capability, requires stored data
  - Representation is key -- what level of abstraction?
  - Maximum leverage of limited perception capabilities

Integration Flexibility & Tight Subsystem Coupling Provide Operational Payoffs



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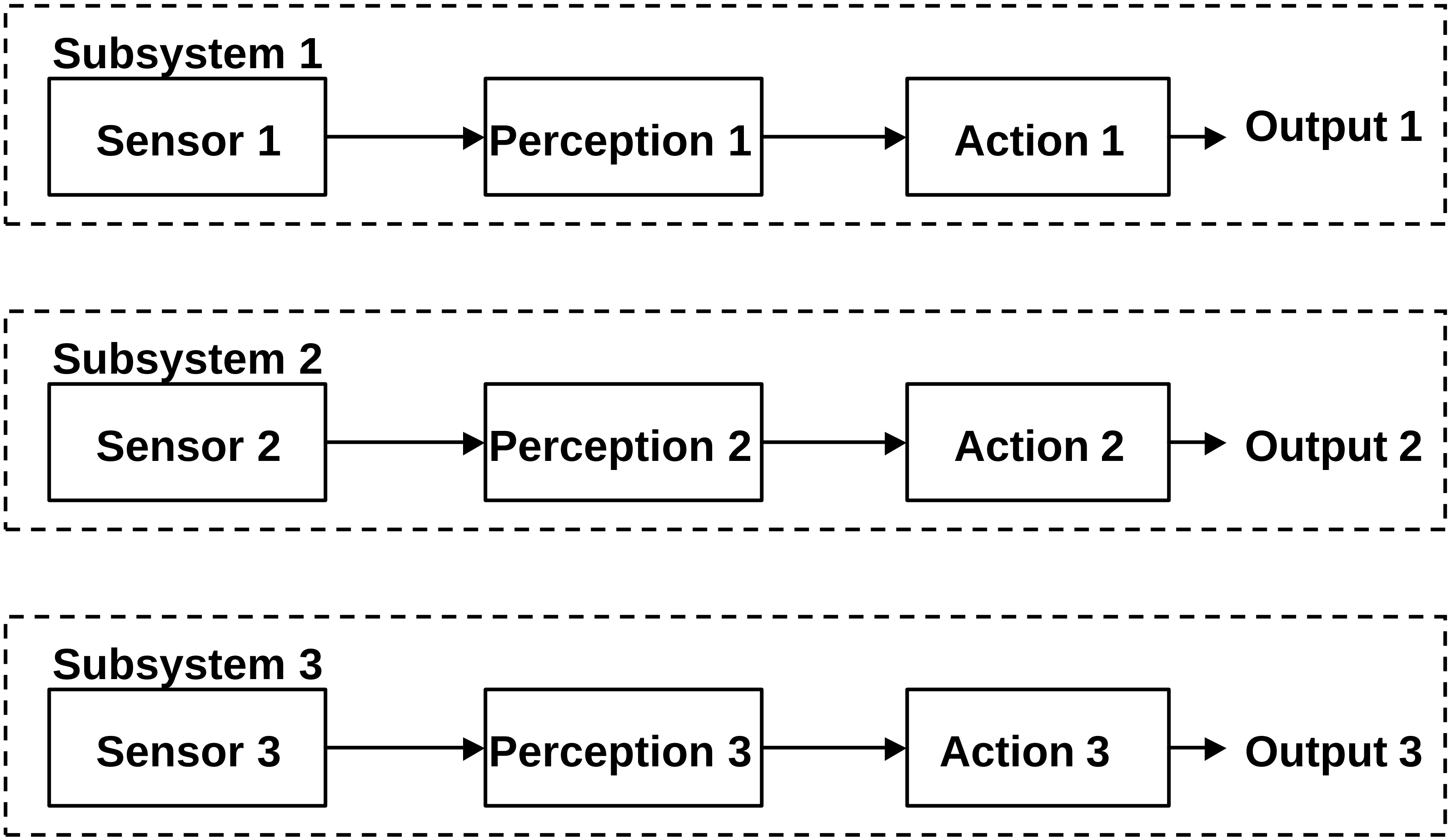
Eliminate Duplication of Sensors and Processing



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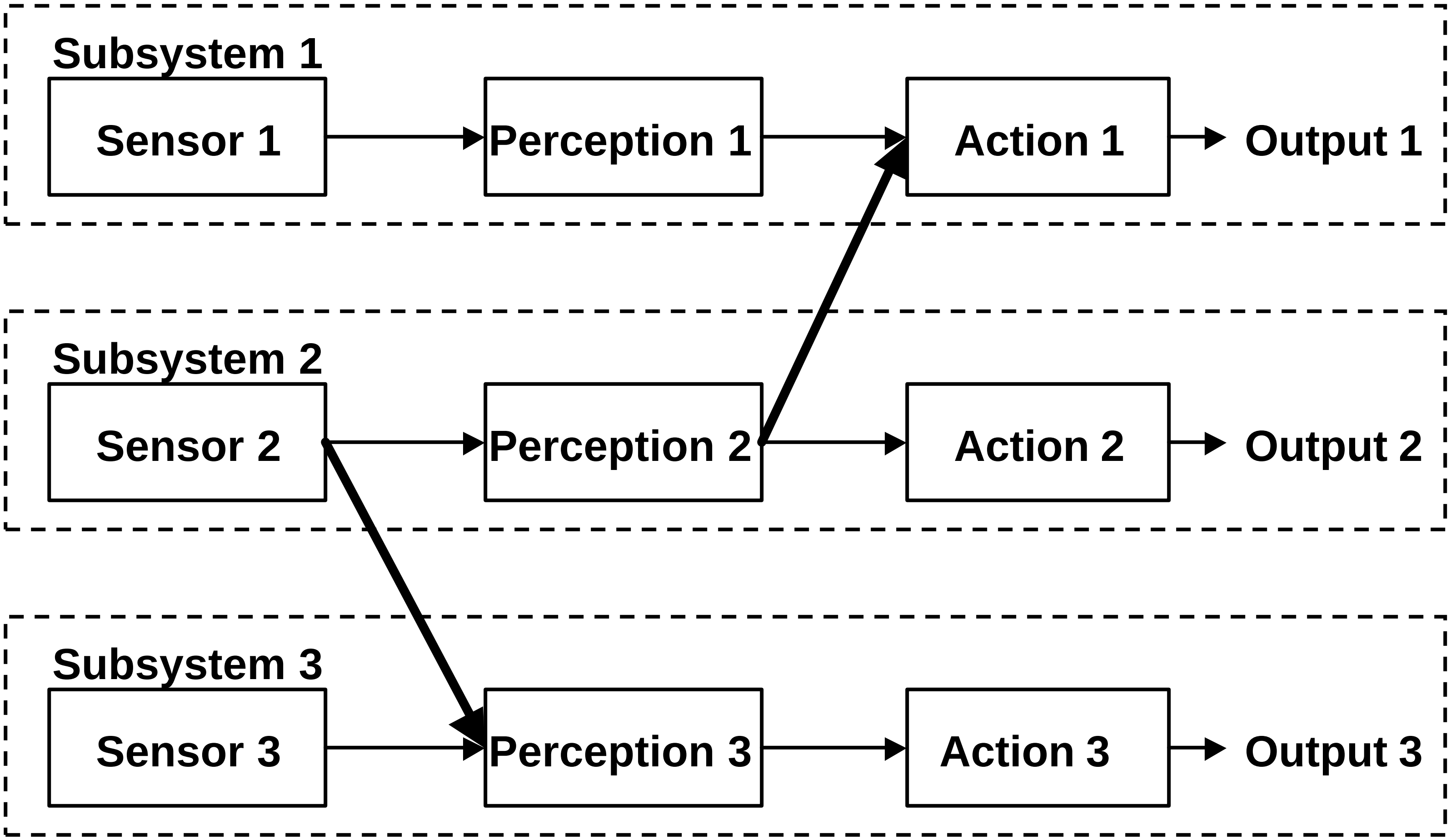

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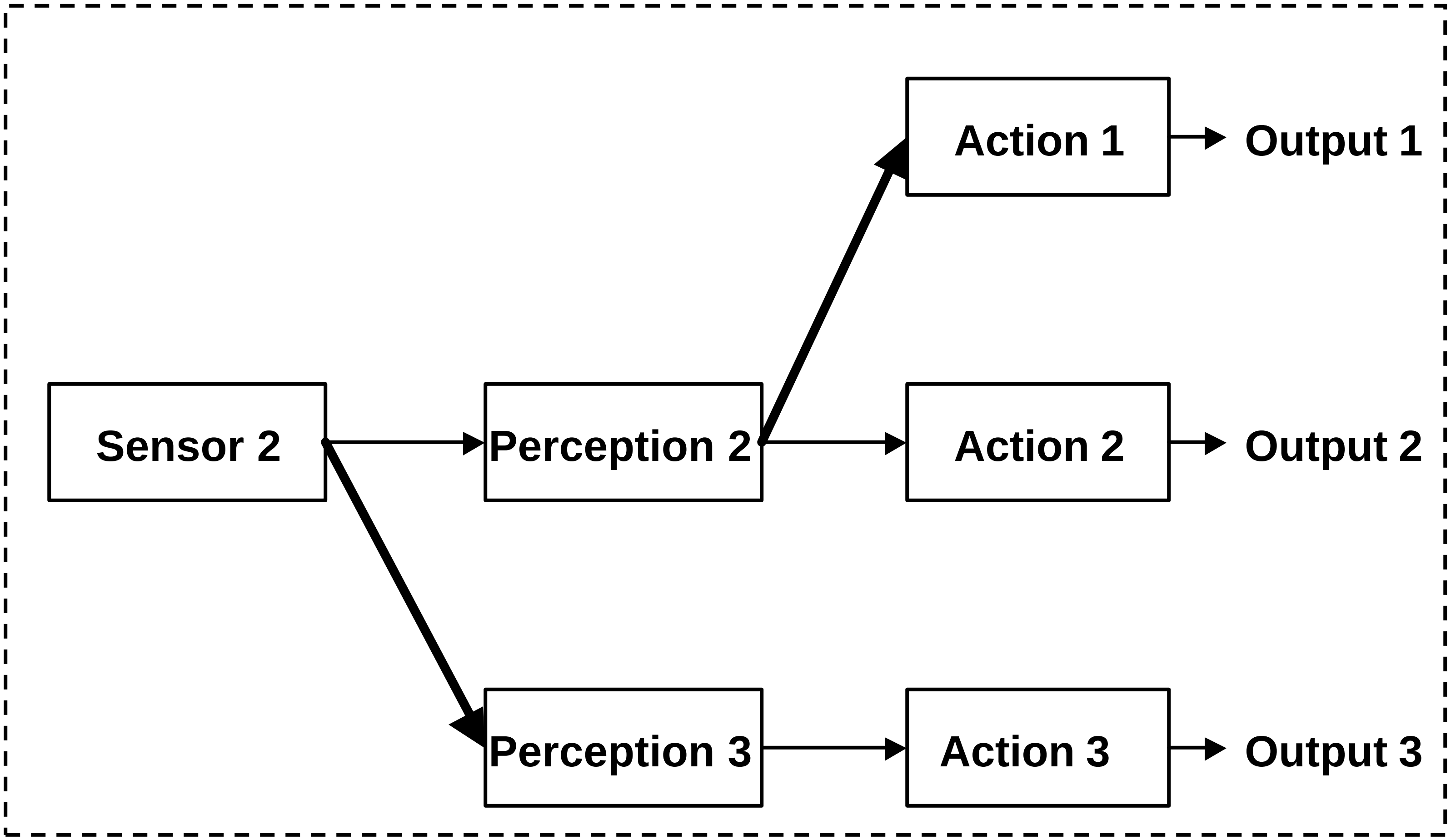
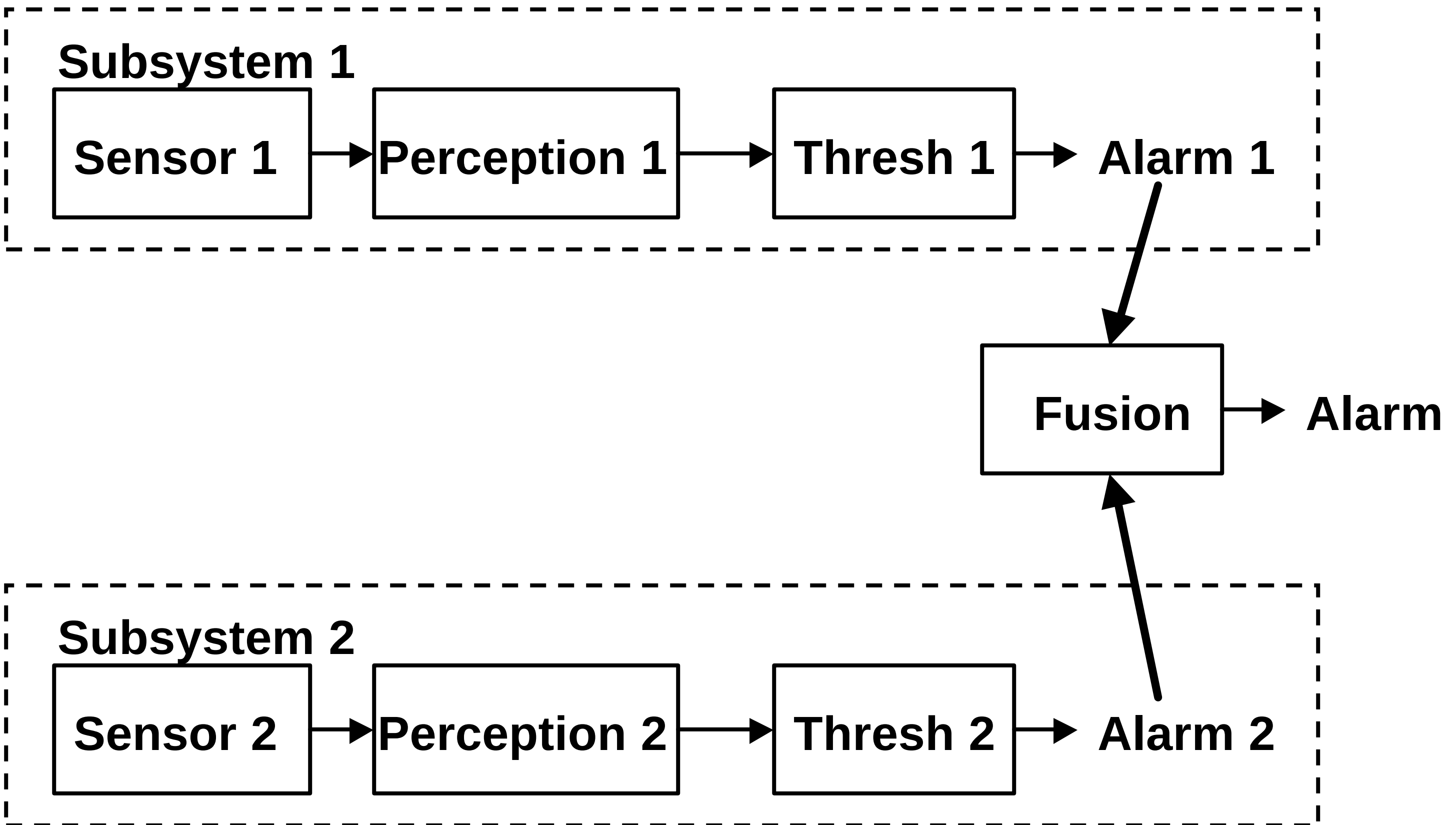
Eliminate Duplication of Sensors and Processing



Defer Alarm Thresholding to Improve Sensor Fusion



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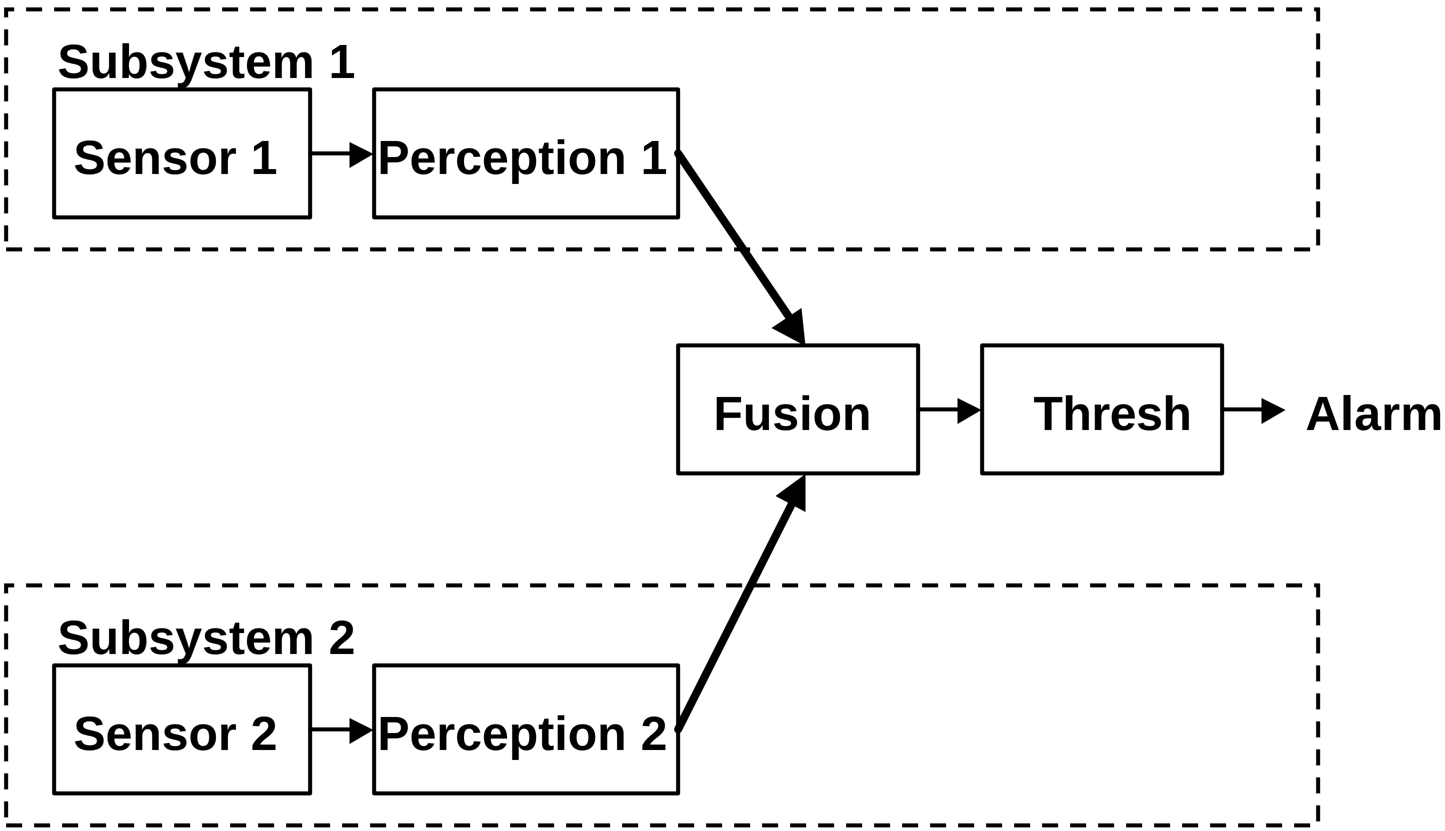
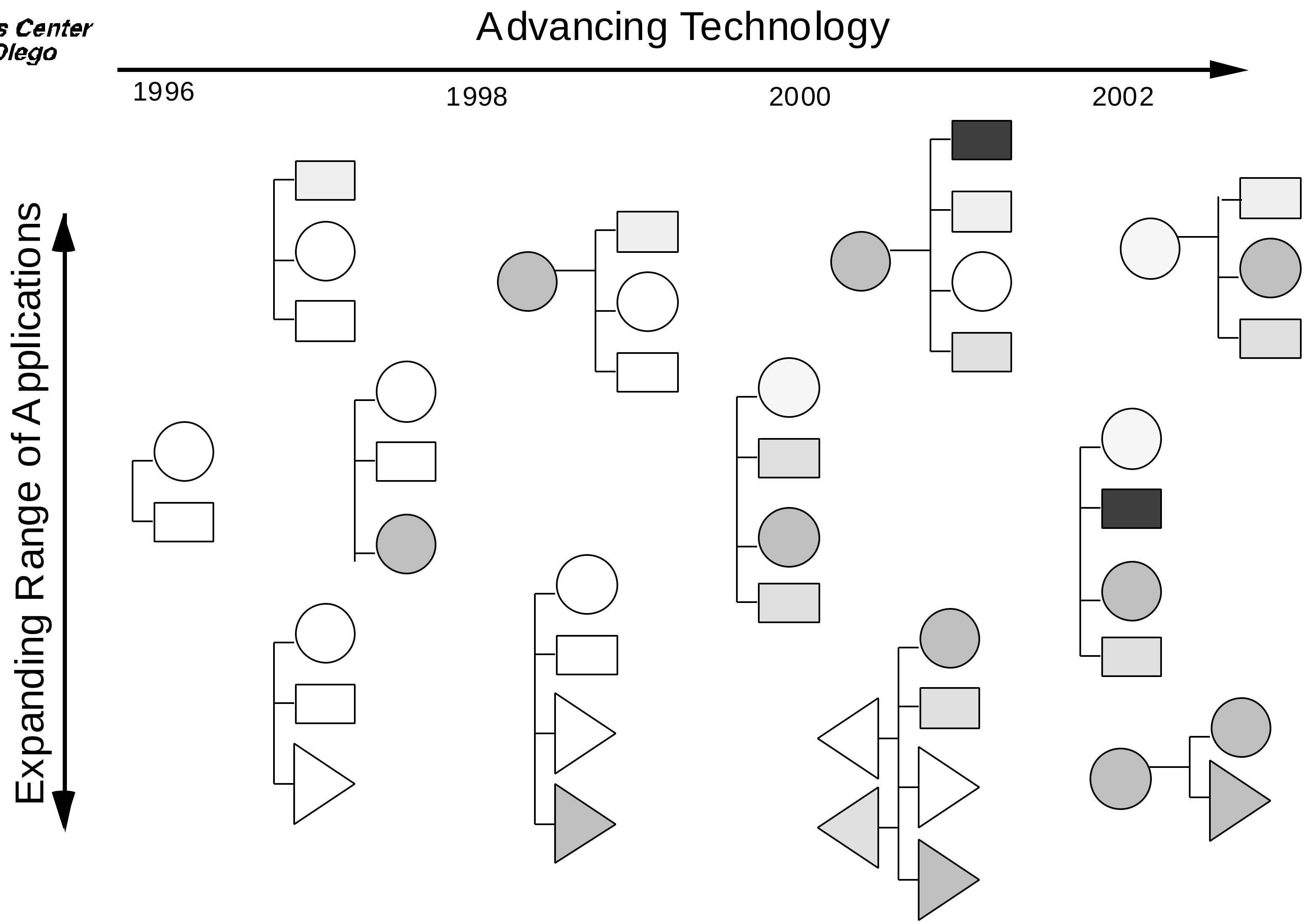


An Evolving Family of Systems



Conclusions

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- Building marketable robots requires both inspiration and perspiration
- Computational Intelligence is only one piece of the puzzle
- While fuzzy logic may be good, fuzzy thinking is definitely bad
- Need to achieve both architectural flexibility and lowest possible system cost
- The “Holy Grail”: vital research programs principally funded by production revenue streams (like ICs and solid state physics), building on very inexpensive mass-produced robotic platforms